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Micro air vehicles are relatively small in size and weight, yielding aircraft that are sensitive to atmospheric wind gusts. In order to reduce gust sensitivity of micro air vehicles, articulation of the main wings attachment to the fuselage to allow flapping is considered. A general and extensible flight dynamic model for articulated micro air vehicles is created where each rigid body of the system is treated as a separate rigid body with 6 degrees of freedom. The system is coupled together by appropriate constraint forces and moments which are determined with a nonlinear constraint controller with guaranteed stability properties so that connection constraints are always obeyed. An attractive feature of the technique is that conventional rigid 6 degree of freedom flight dynamic models can relatively easily be modified to create a multibody flight dynamic simulation tool. This tool is used to investigate gust response for a micro air vehicle. Gusts acting on articulated micro air vehicles result in complex dynamic response which is explored.

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Wing Articulation of Micro Air Vehicles to Reduce Gust Sensitivity

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Abstract

Micro air vehicles are relatively small in size and weight, yielding aircraft that are usually sensitive to atmospheric wind gusts. In order to reduce gust sensitivity of micro air vehicles, articulation of the main wings attachment to the fuselage to allow flapping is considered. A general and extensible flight dynamic model for articulated micro air vehicles is created where each rigid body of the system is treated as a separate rigid body with 6 degrees of freedom. The system is coupled together by appropriate constraint forces and moments which are determined with a nonlinear constraint controller with guaranteed stability properties so that connection constraints are always obeyed. An attractive feature of the technique is that conventional rigid 6 degree of freedom flight dynamic models can relatively easily be modified to create a multibody flight dynamic simulation tool. This tool is used to investigate gust response for a generic micro air vehicle. Gusts acting on articulated micro air vehicles result in complex dynamic response with rigid and articulated aircraft behaving differently.

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I. Introduction

Micro air vehicles are small, autonomous, intelligent aircraft designed to focus on a specific task. The range of applications envisioned for future micro air vehicles in both the civilian and military sectors is impressive. These vehicles provide unparalleled situation awareness and data gathering opportunities in a wide variety of scenarios. While the potential of micro air vehicles is significant, significant technical obstacles must be overcome to realize this potential. A deficiency of current micro air vehicles is their sensitivity to atmospheric wind gusts. Due to their small size and weight, micro air vehicle orientation is highly erratic when operating in gusty atmospheric conditions. Even relatively modest atmospheric gusts cause problematic oscillations in roll, pitch, and yaw of the airframe. This characteristic greatly hampers these aircraft in performing autonomous reconnaissance and targeting missions where steady and stable orientation is required to obtain high quality information.[1]

In this paper, articulation of the major lifting surfaces are considered as a method to reduce gust sensitivity. A schematic of the system under consideration is given as Figure 1. The soft root sections can be physically realized with either a mechanical hinge or a virtual structural hinge. Each hinge is supported with a rotational spring and damper. It is postulated that articulation of the lifting surfaces provides a degree of isolation of the fuselage from aerodynamic moments caused by gusts. Thus, gusts acting on lifting surfaces of the aircraft ultimately affect the fuselage orientation less than a rigid airframe. To examine this type of micro air vehicle from a flight mechanics point of view, a general articulated micro air vehicle flight dynamic model is created and subsequently employed to explore the flight dynamics of an articulated micro air vehicle.

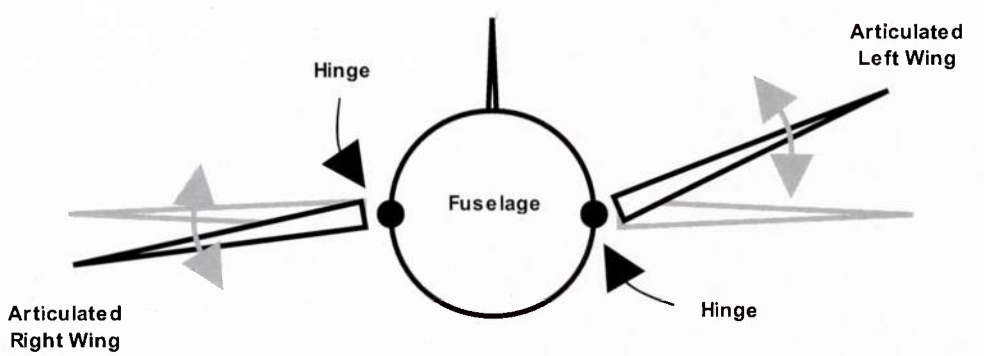

Figure 1 – Front View of Example Aircraft with Articulated Main Wings

II. Articulated Micro Air Vehicle Flight Dynamic Model

A schematic of an articulated micro air vehicle is given in Figure 2. As mentioned above, the air vehicle is modeled as a connected set of N rigid bodies connected by a set of M connection joints. The equations of motion for the system are first generated by considering each rigid body of the system individually as if it were an isolated body with its own 6 degrees of freedom. At this point, all constraint forces and moments that arise from system connectivity are treated as externally applied forces and moments. Of course, the constraint forces and moments are equal and opposite on connected bodies.

For the i th rigid body of the system, the dynamic equations of motion are written in the following form.

$$\dot{X}_i = F_i + G_i U \tag{1}$$

Where X_i is the state vector of the i th rigid body of the system, F_i contains the unconstrained dynamics of the i th rigid body, $G_i U$ represents the contribution of the connection constraint forces and moments to the dynamic equations.

$$X_i = \begin{bmatrix} x_i & y_i & z_i & \phi_i & \theta_i & \psi_i & u_i & v_i & w_i & p_i & q_i & r_i \end{bmatrix}^T \tag{2}$$

$$F_i = \begin{Bmatrix} [T_{IB}^T]\begin{Bmatrix} u_i \\ v_i \\ w_i \end{Bmatrix} \\ [B_{BE}]\begin{Bmatrix} p_i \\ q_i \\ r_i \end{Bmatrix} \\ S_i(\vec{\omega}_{i/I})\begin{Bmatrix} u_i \\ v_i \\ w_i \end{Bmatrix} + \frac{1}{m_i}\begin{Bmatrix} F_{XBi} \\ F_{YBi} \\ F_{ZBi} \end{Bmatrix} \\ -I_i^{-1} S_i(\vec{\omega}_{i/I}) I_i \begin{Bmatrix} p_i \\ q_i \\ r_i \end{Bmatrix} + I_i^{-1}\begin{Bmatrix} M_{XBi} \\ M_{YBi} \\ M_{ZBi} \end{Bmatrix} \end{Bmatrix} \tag{3}$$

Note that I_i is the mass moment of inertia matrix of the i th rigid body about its mass center. Furthermore, the matrix T_{IB} is the transformation from the inertial reference frame to the i th body reference frame while the matrix B_{BE} is the matrix associated with the Euler angle kinematic differential equations. Lastly, the total externally applied forces and moments about the mass center in the i th body reference frame are given as $\begin{bmatrix} F_{XBi} & F_{YBi} & F_{ZBi} \end{bmatrix}^T$ and $\begin{bmatrix} M_{XBi} & M_{YBi} & M_{ZBi} \end{bmatrix}^T$, respectively.

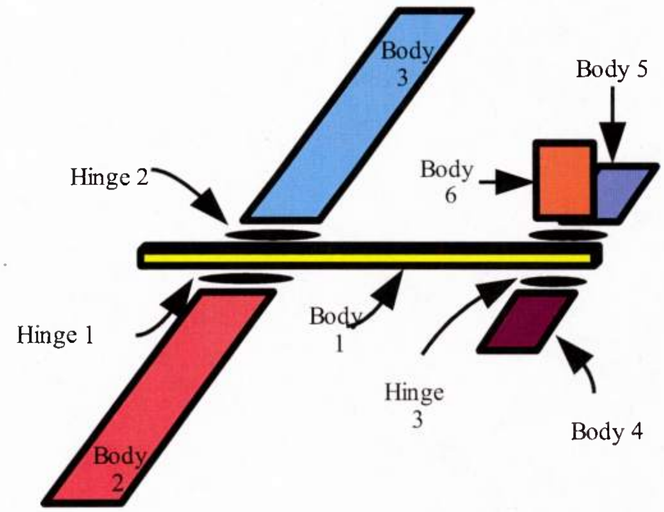

Figure 2 – Multibody Articulated Micro Air Vehicle Schematic

These externally applied loads do not include the effect of connection constraints.

$$T_{IB} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_\phi & s_\phi \\ 0 & -s_\phi & c_\phi \end{bmatrix} \begin{bmatrix} c_\theta & 0 & -s_\theta \\ 0 & 1 & 0 \\ s_\theta & 0 & c_\theta \end{bmatrix} \begin{bmatrix} c_\psi & s_\psi & 0 \\ -s_\psi & c_\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$$B_{BE} = \begin{bmatrix} 1 & s_\phi s_\theta / c_\theta & c_\phi s_\theta / c_\theta \\ 0 & c_\phi & -s_\phi \\ 0 & s_\phi / c_\theta & c_\phi / c_\theta \end{bmatrix} \tag{5}$$

$$S_i\left(\vec{\omega}_{i/I}\right) = \begin{bmatrix} 0 & -r_i & q_i \\ r_i & 0 & -p_i \\ -q_i & p_i & 0 \end{bmatrix} \tag{6}$$

Notice that U from Equation 3 is a vector of connection constraint forces and moments from all the connection elements of the system, not just connections associated with the i th rigid body. The specific form for G_i is a function of the specific connection type. The number of constraint force and moment components is exactly equal to the number of scalar motion constraints that must be satisfied. From a control system design perspective the constraint force and moments and motion constraints form a square system where the number of controls is equal to the number of outputs to be controlled.

For a hinge joint that connects two bodies, relative rotation about the hinge axis is permitted. In order to restrict non allowable motion, in general a set of three constraint force components and 2 constraint moment components exist. The sole purpose of these constraint force and moment components is to ensure that only allowable motions between the two connected bodies takes place. The three constraint force components ensure that the joint position on the connected bodies is the same. The two constraint moment components ensure that only rotation about the joint axis occurs. To express these conditions mathematically, denote the two connected bodies as body A and body B each with an associated reference frame fixed to the body and emanating from the mass center ($\vec{i}_A, \vec{j}_A, \vec{k}_A$ and $\vec{i}_B, \vec{j}_B, \vec{k}_B$). Also, define a reference frame C that has its $\vec{i}_C$ axis along the hinge axis with $\vec{j}_C$ and $\vec{k}_C$ forming a right handed system. Then the two sets of constraint equations are given below.

$$\vec{r}_{O\to A_C} = \vec{r}_{O\to B_C} \tag{7}$$

$$\vec{i}_A \cdot \vec{j}_B = \vec{i}_A \cdot \vec{k}_B = 0 \tag{8}$$

For connection i of the system, these five constraint equations can be put in the shorthand form.

$$e_i = 0 \tag{9}$$

Other joints and connection types can be handled in a similar manner.

The equations of motion for all bodies in the system can be stacked together into one large set of dynamic equations of motion for the system.

$$\dot{X} = F + GU \tag{10}$$

In the same way, the constraint equations can be stacked together to form a large vector of system constraints.

$$E(X) = 0 \tag{11}$$

Note that Equations 10 and 11 represent a set of differential algebraic equations. The vector U contains all constraint force and moment components from all joints in the system and the vector E is a vector of constraint equations that must be satisfied at all times. The number of constraint equations is exactly equal to the number of constraint force and moment components. Recall that the purpose of the constraint equations is to satisfy the constraint equations. Thus, U can be viewed as a control where we seek to solve for U so that it satisfies $E(X) = 0$. If the control system is designed to be stable and begins by satisfying the constraint equations $E(X(t = t_0)) = 0$, then the equations of motion shown in Equation 10 can be integrated with an ordinary differential equation solver and the solution will automatically satisfy all constraint equations.

A key aspect of the dynamic modeling approach above is creation of the constraint force and moment controller. Given the affine nature of the system of Equation 10, a nonlinear inversion controller can be designed. As is customary in feedback linearization control system design, the quantity to be controlled is differentiated until the controls appear. The first derivative of the constraint equation vector is given below.[2]

$$\dot{E}(X) = \frac{dE}{dX}\frac{dX}{dt} = \frac{dE}{dX}F + \frac{dE}{dX}GU \tag{12}$$

For holonomic constraints such as hinge joints, the last term in Equation 12 will be zero. Taking a second derivative of the constraint equations yields.

$$\ddot{E}(X) = \frac{d\dot{E}}{dX}\frac{dX}{dt} = \frac{d\dot{E}}{dX}F + \frac{d\dot{E}}{dX}GU \tag{13}$$

Defining

$$\tilde{F} = \frac{d\dot{E}}{dX} F \qquad \tilde{G} = \frac{d\dot{E}}{dX} G \tag{14}$$

yields the following second order dynamics for the constraint equations.

$$\ddot{E}(X) = \tilde{F} + \tilde{G}U \tag{15}$$

Setting the right hand side of this equation equal to a psuedo control, γ.

$$\ddot{E}(X) = \gamma \qquad \gamma = \tilde{F} + \tilde{G}U \tag{16}$$

The psuedo control is selected so that the constraint equation dynamics are exponentially stable. That means that if the constraint equations have an error initially or numerical roundoff error causes the constraint equations to be slightly violated, then the constraint equations will tend back to satisfying the constraints. If γ is selected in the following manner

$$\gamma = -2\xi\omega_n \dot{E} - \omega_n^2 E \tag{17}$$

then the constraint equation dynamic equations become

$$\ddot{E} + 2\xi\omega_n \dot{E} + \omega_n^2 E = 0 \tag{18}$$

which is of course a simple damped oscillator. By picking the damping ratio and the natural frequency properly the constraint equations dynamic equations are stable. This is a standard feedback linearization controller where the zero dynamics represent the dynamics of the properly coupled physical system.

III. GENMAV Aircraft Description

In order to investigate the potential of articulated micro air vehicles, both rigid and articulated micro air vehicles are compared and contrasted using the flight dynamic modeling approach discussed above.

Physical Aircraft

As a representative model to investigate the effects of an articulated wing structure, the GENMAV aircraft as designed by the US Air Force Research Laboratory was employed. This aircraft was designed as a generic micro air vehicle to be used as a baseline air vehicle for research efforts. GENMAV has a conventional tail and a high wing design. The wing has a span of 24 inches and a mean chord of 4.78 inches.

The basic aerodynamics of the GENMAV were found with Athena Vortex Lattice (AVL) aero prediction code. The basic GENMAV aircraft was modified to have articulated wings by first splitting the main wing in the middle and adding hinges at the intersection of the fuselage and the individual wing halves as seen in Figure 4. Linear springs were added inside the fuselage to create a first class lever with the hinge as the fulcrum. Damping material can be added to change the damping characteristics of the hinge. The mass of the articulated version of the articulated GENMAV is 0.8629 kg. The articulated GENMAV aircraft is modeled as 3 independent bodies (Body 1 = Fuselage and Tail; Body 2 = Left Main Wing; Body 3 = Right Main Wing) and the aerodynamics for each body are calculated separately.

Figure 3 – GENMAV Micro Air Vehicle

For the wings, strip theory is used with 13 wing sections to calculate the aerodynamic forces and moments. The fuselage uses only one section. Control of the GENMAV aircraft is performed with two elevons on the horizontal tail surface and with throttle control of the nose mounted motor and propeller. This allows for a pitch, roll and slight yaw moment to be imparted to the aircraft as well as thrust.

Figure 4 – Main Wing Hinge for Articulated GENMAV Aircraft

Autopilot

The autopilot for the GENMAV is the Kestrel Autopilot System which is based on linear PID control. For the simulation model only the cruise PID blocks were included as this is the flight condition simulated. A low pass filter is added to the derivative control calculation to reduce noise and integrator windup is prevented by accounting for the clipped control input when calculating the error integral. Throttle control is generated by running airspeed error through a PID block with a limited output. The limited airspeed error PID block output is added to a feed forward term comprised of nominal trim airspeed and throttle values. Aircraft elevator control is generated by first running altitude error through a limited PID block. The output of this limited block plus the nominal trim angle of attack creates a desired or commanded pitch angle. Using the commanded pitch attitude, a pitch angle error signal is generated and subsequently run through a limited PID block. The output of the pitch angle error limited PID block is discounted with yaw rate to form a final elevator command. Aircraft aileron control is generated by first running heading error through a limited PID block. The output of this limited block creates the commanded roll angle. Using the commanded roll attitude, a roll angle error signal is generated and subsequently run through a limited PID block. The output of the roll angle error limited PID block form the aileron command.

IV. GENMAV Aircraft Simulation Results

In order to investigate the potential of articulated micro air vehicles, the GENMAV aircraft was simulated performing a variety of maneuvers and vertical gust profiles with various different hinge stiffness and damping configurations. The response of this multibody dynamic system is complex, particularly as it couples with the aircraft autopilot. A rigid and articulated GENMAV generally respond differently to the same gust excitation. Figures 5 and 6 present a single example case where the aircraft is flying straight and level with the autopilot engaged and suddenly encounters a 1.5 m/s vertical sharp edge gust located along the right side of the aircraft. After the aircraft hits the gust, it rolls left wing down and turns away from the gust, quickly departing the gust area. Due to flapping caused wing dihedral, the articulated configuration quickly settles in roll and yaw yielding smaller lateral position perturbations than the rigid configuration. However, depending on the hinge design, autopilot gains, and the gust encountered response of the articulated configuration can be slower than the rigid configuration. Figure 7 shows constraint equation residuals for both the position and orientation constraint equations. It is important to note that all constraints are satisfied to high numerical precision. Figure 8 plots the effect of hinge stiffness on the response on lateral position response and pitch angle response. Notice that as the hinge spring stiffness is increased beyond 70 N m /rad perturbation of the aircraft after impacting a gust levels indicating that the aircraft is approaching rigid behavior.

V. Conclusions

Micro air vehicles are relatively small in size and weight, yielding aircraft that are usually sensitive to atmospheric wind gusts. In order to reduce gust sensitivity of micro air vehicles, articulation of the main wings attachment to the fuselage to allow flapping is considered. A general and extensible flight dynamic model for articulated micro air vehicles is created where each rigid body of the system is treated as a separate rigid body with 6 degrees of freedom. The system is coupled together by appropriate constraint forces and moments which are determined with a nonlinear constraint controller with guaranteed stability properties so that connection constraints are always obeyed. An attractive feature of the technique is that conventional rigid 6 degree of freedom flight dynamic models can relatively easily be modified to create a multibody flight dynamic simulation tool. This tool is used to investigate gust response for a generic micro air vehicle. Gusts acting on articulated micro air vehicles result in complex dynamic response with rigid and articulated aircraft behaving differently.

VI. References

1. M. Costello, "Challenges Facing Micro Air Vehicle Flight Dynamics and Controls Engineers," Paper Number AIAA ASM 2008-0521, Proceedings of the 2008 AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 2008.

2. J.J. Slotine, W. Li, Applied Nonlinear Control, Prentice Hall Incorporated, Englewood Cliffs, New Jersey, ISBN 0-13-040890-5, 1991.

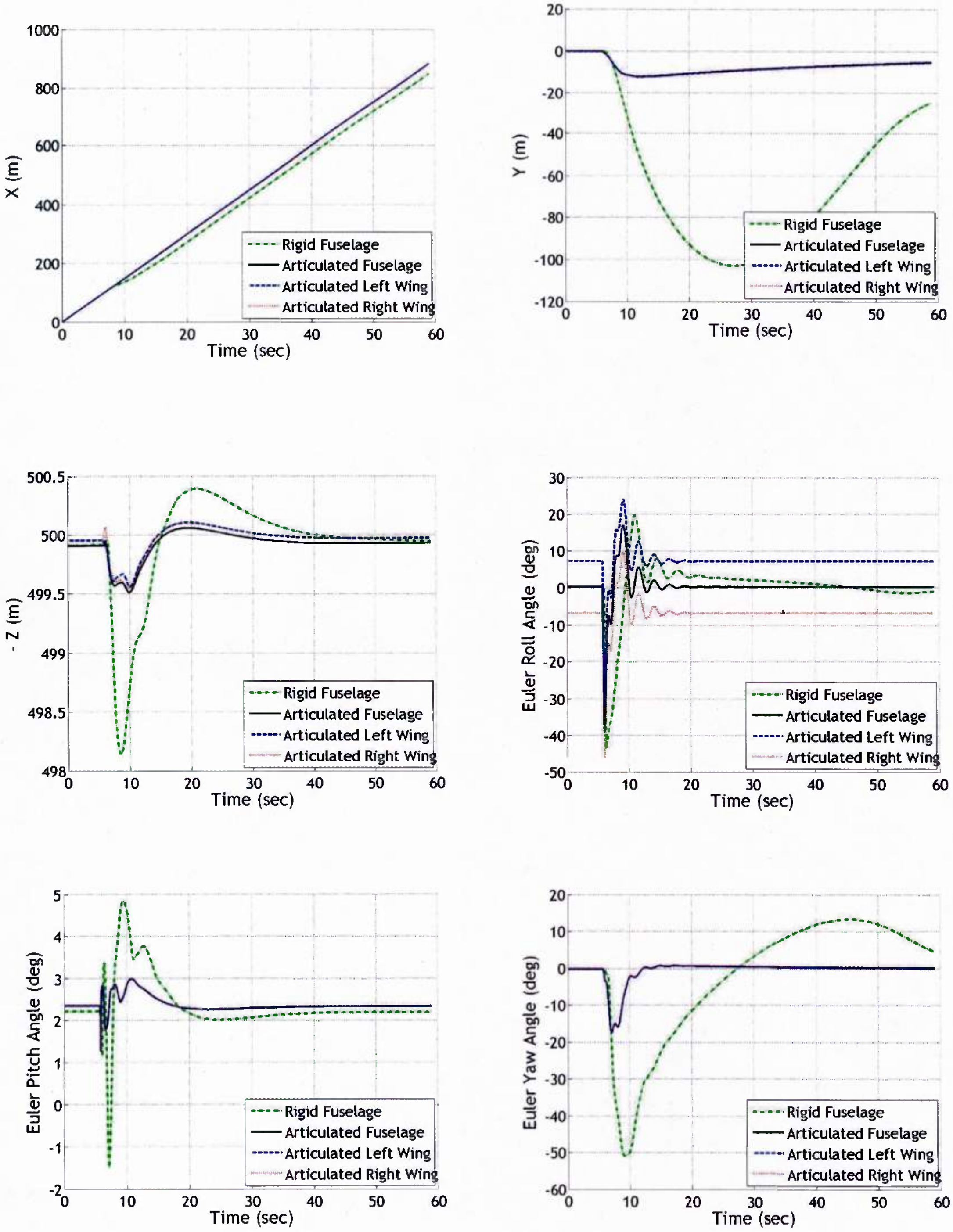

Figure 5 – Example Simulation of Position and Orientation of GENMAV Aircraft

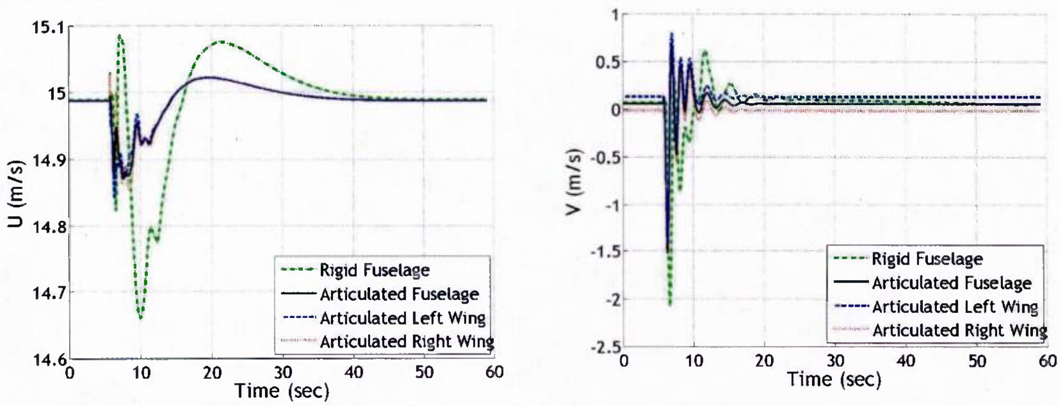

Figure 6 – Example Simulation of Velocity of GENMAV Aircraft

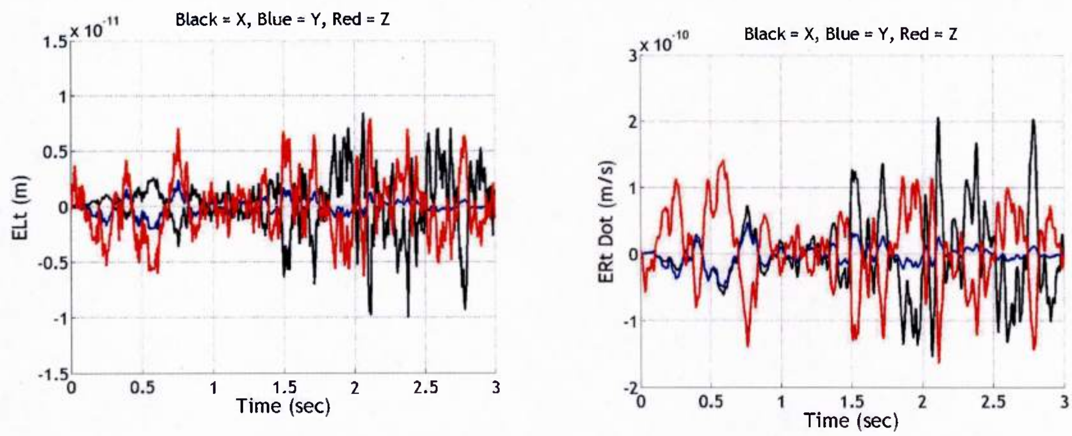

Figure 7 – Example Simulation of Constraint Equation Residuals

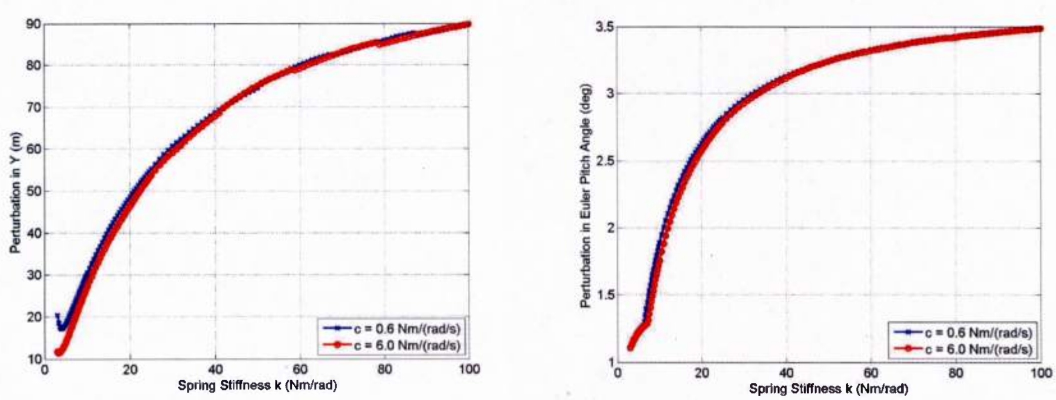

Figure 8 – Effect of Hinge Spring Stiffness